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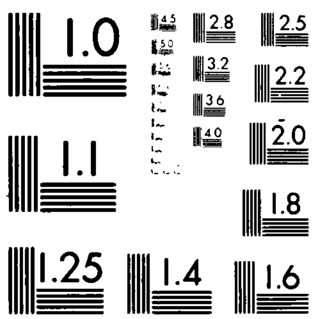

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AN INVESTIGATION OF SENSORS SUITABLE FOR MONITORING BLADE DEFLECTIONS FOR A VA1310 WIND TUNNEL COMPRESSOR

Donald S. Wilson
SHAKER RESEARCH CORPORATION
NORTHWAY 10 EXECUTIVE PARK
BALLSTON LAKE, NY 12019

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FLIGHT DYNAMICS LABORATORY
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WRIGHT-PATTERSON AIR FORCE BASE, OHIO 45433

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Gary A. Dale

GARY A. DALE
Mechanical Systems Group
Experimental Engineering Branch

Joseph M. Hample

JOSEPH M. HAMPLE, Chief
Experimental Engineering Branch
Aeromechanics Division

FOR THE COMMANDER

Alfred C. Draper

ALFRED C. DRAPER
Acting Chief, Aeromechanics Division
Flight Dynamics Laboratory

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Stator	Instrumentation	Inductance Probe	
Blade Vibration	Optical Probe	Eddy Current Probe	

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This work is a continuation of a contract to identify and develop a cost effective, reliable procedure for determining potential compressor blade failure in time to prevent the actual failure. The first phase of the contract proposed a system that utilizes non-contacting blade tip monitoring probes, a microprocessor and a host computer while this second phase concentrated on probe evaluation. Both static and dynamic tests were conducted to determine probe sensitivity, diameter of resolution and rise time. From

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the results of the laboratory evaluations of probes commercially available it is apparent that a probe is not available that will meet all of the requirements for blade monitoring in the Allis-Chalmers VA1310 compressor. A Hewlett-Packard HEDS 1000 optical probe had the required static and dynamic characteristics, but was limited in operating temperature. A Weigand Wire Probe offered considerable promise in terms of reliability, long-term stability and temperature resistance, however it did not have the required dynamic characteristics.

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1.0 INTRODUCTION

A serious problem occasionally encountered in axial flow compressors is blade cracking and ultimate failure. Should a blade fail in the early compression stages, fragments passing through the machine can cause considerable damage. To protect against such an event requires a system that can detect impending blade failure before actual failure occurs. In order to study the feasibility of such a system, a program was conducted (as reported in Reference 1) that outlines a potential technique for monitoring blade integrity. The system was based on measurement of blade twist induced by cracking at the blade root. A design concept was developed for application to an Allis-Chalmers ten-stage, axial flow compressor, Model VA1310.

As a result of the earlier study it was concluded that the probe used to detect blade twisting was the most critical element in the system. Performance requirements for the probe are very stringent and the capabilities of currently available probes to meet these requirements are questionable. The purpose of the work discussed in this report is to review the characteristics of existing probes and probe techniques in an attempt to select a sensor capable of the requirements of the blade monitoring system described in Reference 1.

2.0 DISCUSSION

The Allis-Chalmers VA1310 compressor is an 8500 HP, ten-stage axial flow compressor operating at a nominal speed of 3600 rpm used for a wind tunnel installation at Wright-Patterson Air Force Base. The construction of the compressor is a drum type rotor of constant diameter of 38 inches (0.965m) and decreasing blade height. Blade rows 1 - 4 contain 37 blades of the same design but different lengths for each row and rows 5 - 10 contain 47 blades using a second blade configuration of decreasing length per stage; Figure 1 illustrates both blade configurations. Inlet temperature to the compressor is 100°F (37.8°C) with an outlet temperature of 465°F (240.6°C) maximum.

Reference 1 summarizes the results of a study conducted to design a system capable of protecting the compressor from an impending blade failure due to blade cracking. The system approach selected was to monitor the blades for a change in angular twist resulting from a crack at the blade root. The system requires the use of two non-contacting probes for each blade row, mounted radially to detect the passage of the leading and trailing edge of each blade as illustrated in Figure 2. Any difference in the time of arrival of the leading and trailing edges of a blade by the probe is indicative of blade twisting. It is quite apparent that the ability to detect blade twist due to a crack at the blade root is quite dependent upon the capabilities and characteristics of the probes used for monitoring the blade. The following paragraphs summarize the results of a study conducted to determine the availability of a probe capable of meeting the requirements for monitoring the blades in the VA1310 wind tunnel compressor.

2.1 Probe Requirements

In order to establish application requirements for a blade monitoring probe, an analysis was conducted on the influence of a crack at the blade root for the first stage blade (longest blade) and tenth stage blade (shortest blade). The angular blade deflection as a function of root stress was calculated to determine the range over which a probe must operate to detect a crack prior to failure. Figure 3 is a plot of the change in the combined torsional, bending and tensile stresses in the blade root as a crack developes. Stress is plotted as a function of the angular displacement of either the leading

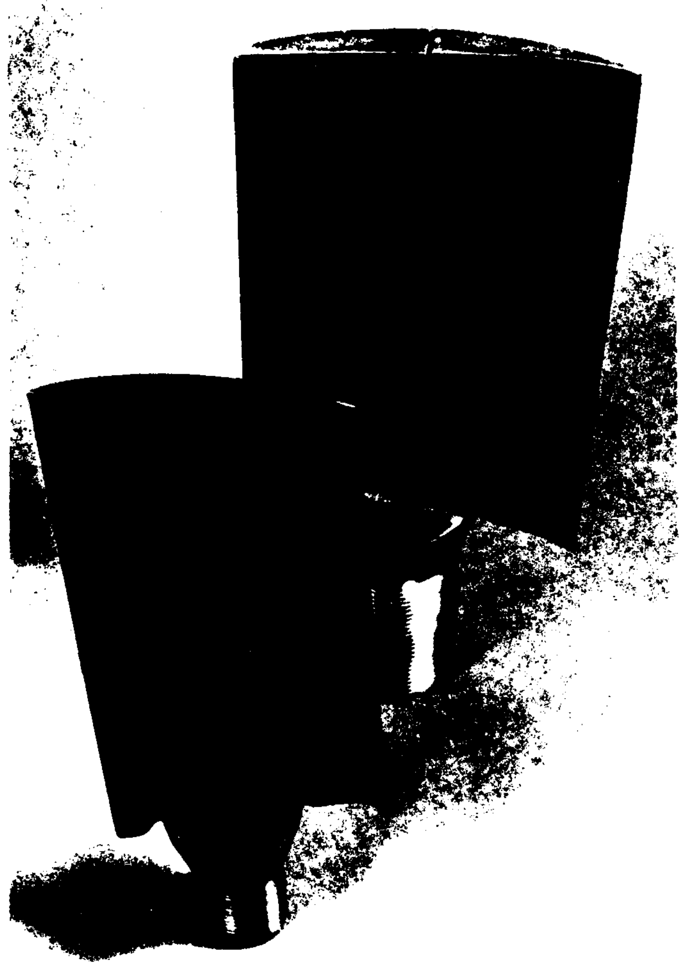

Figure 1 First and Fourth Stage Blades for VA1310

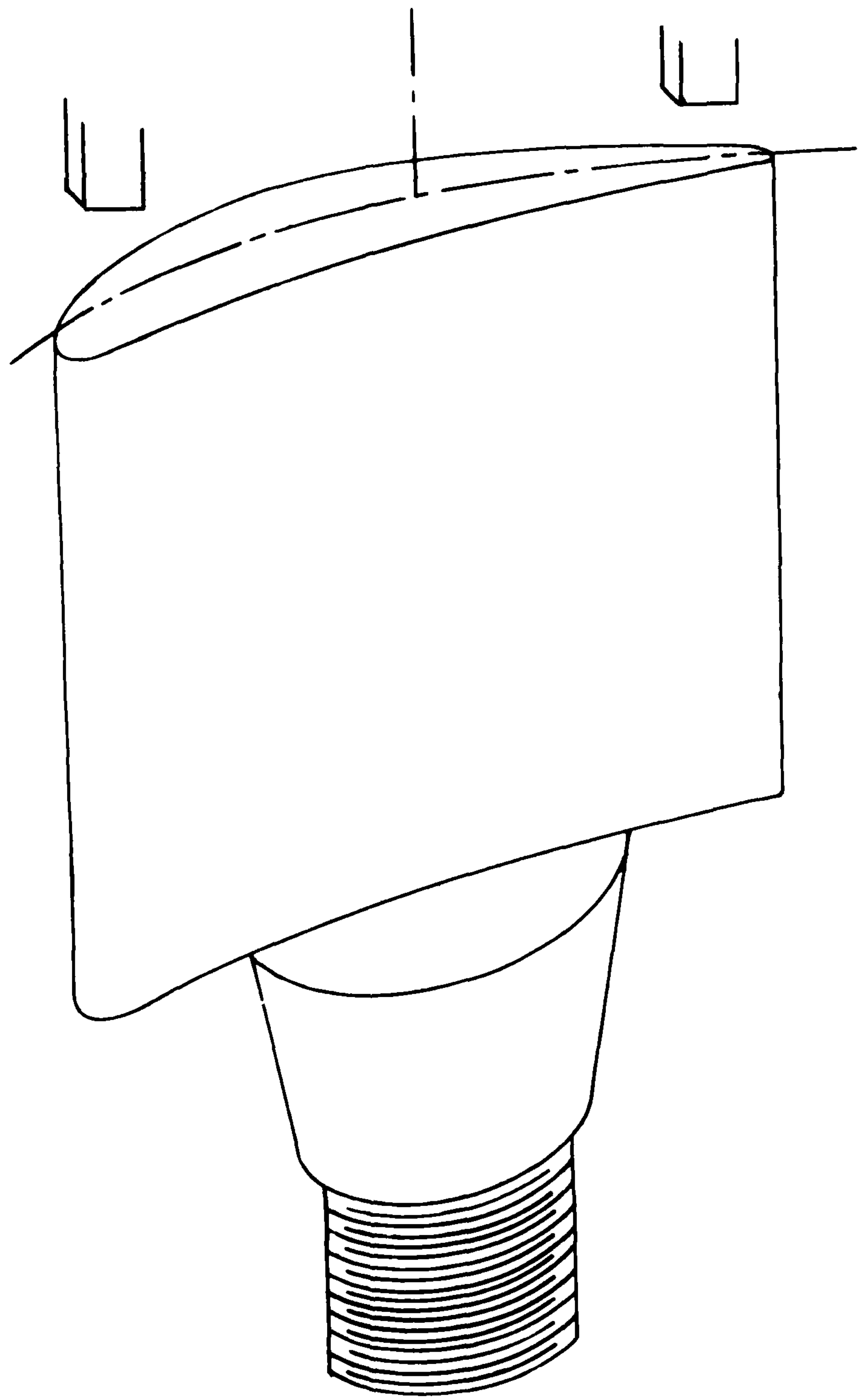

Figure 2 Typical Probe Locations for Monitoring Blade Twist

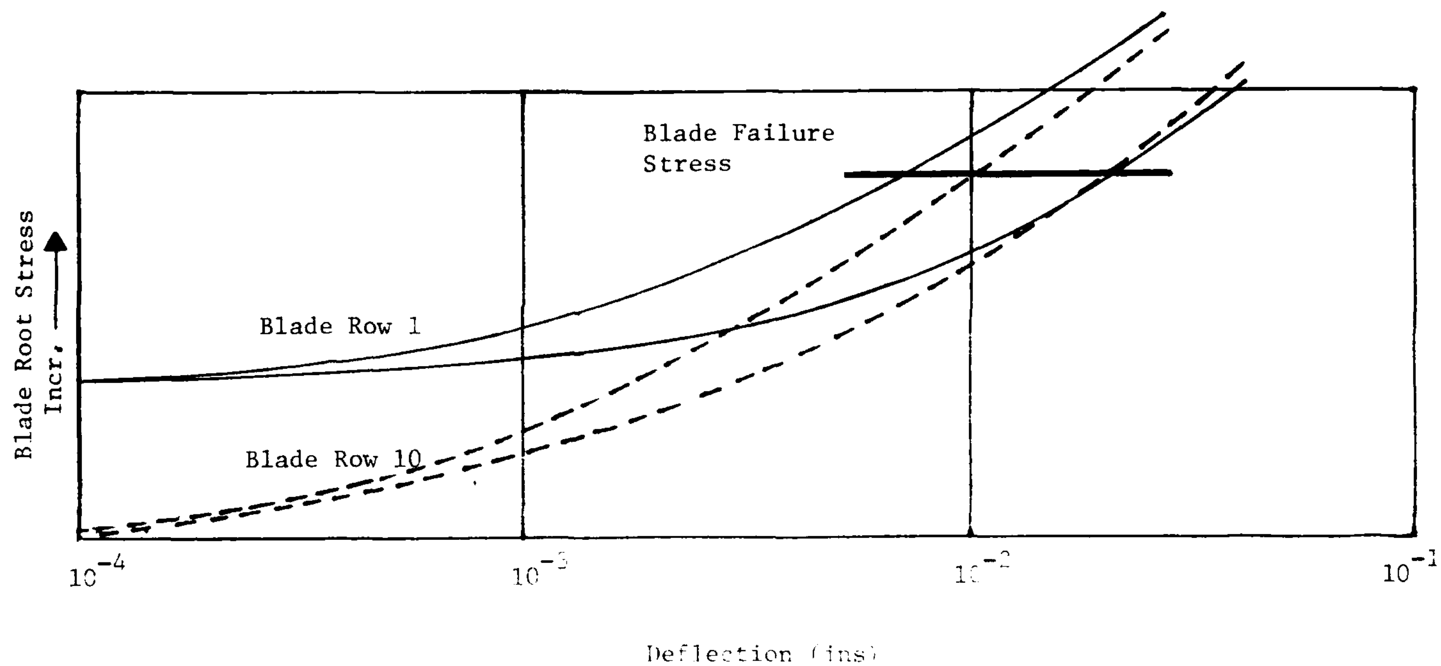

Figure 3 Influence of Blade Root Cracking on Blade Angular Deflection

or trailing edge of the blade tip for the first stage blade and the tenth stage blade. A range of angular displacements are shown for each blade representing crack growth in the x and y planes of the root. Blade breakage is assumed to occur at 65000 psi combined stress. The results of this analysis is summarized in Table 1.

Table 1

BLADE TIP DEFLECTION IN THE ANGULAR DIRECTION AT FAILURE

Blade	Deflection Ranges (ins.)
1	0.0075 - 0.023
10	0.010 - 0.020

At best, it would be desirable to detect deflections of ten percent of the deflection at failure and as a minimum, deflections of fifty percent of the failure deflection is required. This implies that a sensor detecting the approach of the leading edge of a blade at the blade tip should be capable of determining blade position within 0.00075" as a maximum and 0.00375" as a minimum. At 3600 rpm of the compressor the blade tip surface velocities of blade row 1 and 10 are 9916 ins. per second and 8404 ins. per second respectively. Time resolution required for the probe, therefore, is 75.6 nanoseconds maximum to 378 nanoseconds as a minimum. The corresponding frequency response of the probe must be in the range from 2.6MHz to 13.2MHz. Probe time resolution is the single most difficult requirement for the probe.

A second consideration for probe installation is the stand-off gap between probe and blade tip. The nominal assembled tip clearance between the blade and the casing is 0.080 in. to 0.100 in. It would be desirable to locate the probe flush to below the case to prevent probe damage. Centrifugal growth of the compressor drum at 3600 rpm is 0.018 inch radially. Additionally blade growth of the first stage blade is 0.0015 inch radially, ignoring any growth in the blade anchor region. With the probe mounted flush in the case, the probe should operate with a gap clearance in the

range of 0.060 to 0.080 ins. Smaller gaps could be tolerated, with 0.040 ins. considered the minimum safe gap.

The ambient temperature range requirement for the probe is 60°F to 460°F.

2.2 Literature Review of Detector Techniques

In order to determine the type of probe most suitable for blade tip monitoring experience as reported by others in literature, as well as reported capabilities of available sensors were reviewed. The principal probe characterisitc of concern in reviewing data is the probe resolution time which was stipulated in Section 2.1 as 75.6 ns to 378 ns. It is anticipated that actual time lag measurements should be an order of magnitude better than this or 7.5 ns to 37.8 ns. This is a measure of the rise time requirements for the probe.

Any type of non-contacting proximeter type probe, i.e. capacitive, inductive or optical, could be considered as potential candidates. Roth(2) reported that tests run on microwave probes, inductive probes and capacitive probes resulted in poor rise time characteristics because of the required probe to blade stand-off distance needed for safety reasons. He, therefore, considered these techniques unsuitable for resolutions below 100 ns. He concluded that optical techniques were most suited and utilized an He-Ne laser and optical fibers. A single fiber and lens system was used to focus the light on the blade tip with a focus diameter of the same magnitude as the smallest measureable amplitude. Reflective light from the probe was picked up through the lens to the reception fibers. This system was evaluated and proved satisfactory to blade angular deflections to 0.008 ins.

Stäheli(3) evaluated blade vibration by installing a small permanent magnet in the tip of a blade and using a meander shape winding installed in the stator as an inductive pickup. Frequency modulation of the output voltage was indicative of blade vibration. This system was also employed to measure blade twist. Two magnets, one each in the leading and trailing ends of the blade tip were employed, and two pickup wires were used to measure the phase difference between the induced voltage in both pickups. The results of ex-

perimental tests for measuring blade twists yielded scatter of ±0.05° of twist. The measurement accuracy required in the VA1310 compressor is 0.05° with maximum twist prior to failure of 0.22°.

Bien and Camoc [4] discussed the use of two reflective laser beams and interferometry to monitor blade motions. Retroreflectors were attached to the rotating member to return the transmitted beam back to the source. The system discussed was used to measure blade vibration and not static twist of the blade. Fringes were created by motions of retroreflectors in a plane normal to the laser beam. For measuring blade twist, this implies that the laser beam would have to be directed at the blade normal to the blade surface rather than radially observing the tips. Accuracies of the systems used in this manner were reported as measuring angular vibrations to one millirad which is the equivalent to an angular displacement of 0.0004 in. on a four-inch wide blade. It was also pointed out that vibration of the blade is being measured, all the information is contained in the fringe intensity modulation frequency and therefore variations such as particles, laser power and temperature gradients have a negligible effect. In the case of using interference measurements for static twist, these effects can be very important.

A similar technique to using light interference fringes is the use of a laser doppler system described by Kulczyk, etc.[5]. The laser is located in a plane normal to the blade surface and the doppler shift due to blade motion is measured. This system was also used for vibration measurements rather than static deflection measurements and provides information regarding the vibratory frequencies only. The system is sensitive to surface reflectivity changes and surface conditions.

An optical reflective system directed at the blade tips was evaluated by Nieberding and Pollack[6]. A tungsten filament lamp was used as the light source, focused through a lens 0.59 in. from the blade tip on a diameter of view of 0.0275 in. Reflected light was collected through a lens into two noncoherent fiber optics bundles. Reported flutter in this system was reported as 500 ns resulting in amplitude variations of 4.3 m rads. In the proposed system for the VA1310 compressor on a four-inch wide blade this would result in an angular displacement error of 0.0086 in. It was pointed

out that improvements in the noise level were sought by decreasing the minimum pulse rise time of the probe. Like most of the other investigators, the experimental effort was directed toward determination of vibratory amplitudes but is also applicable to static angular twist measurements of blades. Further evaluations of this system by Kurkov and Dicus[7] indicated that special care was taken to avoid occasional spurious signals which were probably due to air particle contamination.

A number of different sensing technqiues were evaluated in a report by Hegner[8]. This effort was directed toward detection of foreign object induced damage to blades during operation. An eddy current type pickup was used to compare variations in spacing between blades but was limited in accuracy to the blade spacing accuracy. An electromagnetic reflective wave technique using two sensors for measurement of reflective wave phase change. The system was capable of detecting defects in the 0.02 to 0.03 in. range. It was pointed out that the excitation frequency was 88 GHz and reliable operation of components in this frequency range was questionable.

Two eddy current type probes were also evaluated by Hegner[8] to measure blade twist angle. The probes were driven by a 10 MHz excitation frequency and produce angle measurements of blade twist to 35 m rads. It was pointed out that the probe did not use a resonant circuit and detection of a shift in resonant frequency, as is common in eddy current probes. This is due to the 10 MHz requirement. At this high excitation frequency slight variations in probe capacitance or inductance due to temperature variations could cause considerable drift in a resonant circuit.

The experience reported in literature on sensors used for monitoring blade motions is summarized in Table 2. Most investigators selected optical techniques because of the higher response times possible. Comments reported regarding the application of optics include sensitivity to surface conditions and reflectivity changes, occasional spurious signals from dust and concern over the special training for operating and maintaining these systems. The optical techniques were all developed under laboratory conditions. In their present configurations they were generally not considered suitable for a long term continuous monitoring system. The use of eddy current detection

TABLE 2

SUMMARY OF SENSOR CAPABILITIES FOR BLADE DISPLACEMENT MEASUREMENTS (From Literature)

REFERENCE	TECHNIQUE	PROBE DIRECTION	MEASUREMENT ACCURACY	REMARKS
VA1310 Compressor		Radial	.001"/.003"Tip Defl 75/378 ns resp. .27/.8 m rads	Probe Requirements
Roth(2)	Microwave Capacitive Inductive Laser/Fiber Optics (Reflective)	- - - Radial	- - - .008 Tip Defl. >100 ns.resp.	Not selected - Output rise time greater than 100ns. Requires spl. Training for oper. maint.
Stäheli(3)	Perm.Magnet in blade tip	Radial	±0.5 m rads	
Bien & Camac(4)	Interferometry	Normal to Blade	1 m rad	
Kulczyk(5)	Laser-Doppler	Normal to Blade	Vibration freq. only	Sensitive to reflectivity changes & surface conditions
Nieberding & Pollack(6)	Fiber Optics (Reflective)	Radial	500 ns. 4.3 m rads	Sensitive to dust
Hegner(8)	H.F.Reflective wave Eddy-Current	Normal to Blade Radial	.02"/.03" Blade defect 35 m rads	Component reliability questionable in 88GHz range 10MHz excitation frequency
McCarty & Thompson(9)	Fiber Optics (Reflective)	Radial	500 ns. 4.3 m rads	Sensitive to dust

techniques were reported as suitable for long term reliable operation, although the response time and resolution was limited.

2.3 Market Survey of Detector Techniques

In reviewing the availability of proximeter type probes suitable for monitoring blade motions, the primary candidates considered were:

- Capacitive probes
- Inductive and eddy-current probes
- Optical probes
- Wiegand wire probe

2.3.1 Capacitive Probes

Proximeter type probes based on the capacitor principle utilize the probe tip as one plate of the capacitor and the blade to be sensed as the second plate. The air gap between plates functions as the dielectric. Variations in the air gap produce a change in capacitance which is converted into an output voltage. For operation, the probes require a carrier frequency. Since frequency response in the range of 2.6MHZ to 13.2MHz is required, carrier frequencies should be approximately an order of magnitude greater than this. Several manufacturers of capacative probes were found. The highest carrier frequency found was 3MHz providing a frequency response of 300KHz. The use of the capacative principle for the present application would require development of a special probe.

Use of a capacative probe presents a second problem. A parallel plate capacitor has a capacitance value that varies with both plate area and distance; ie:

$$C = \frac{KA}{4\Pi\ S(9x10^5)}$$

where C = microfarads
A = plate area $(cm)^2$
S = plate separation (cm)

In order to maintain a small area of resolution that the probe observes the plate diameter must be of the same order of magnitude as the measured angular deflection. This results in extremely small values of capacitance of the same order as the capacitance of the wire connecting the plate to the circuit components. To compensate for this small capacitance, the distance between plates (S) must be very small. The resulting small required gaps exceed the runout tolerances of the blade tips making this approach unsuitable.

2.3.2 Inductance and Eddy-Current Probes

Inductive probes are based on the principle of the inductance of a coil changing in the presence of ferromagnetic objects. If the coil is part of a resonant circuit, a shift in resonant frequency or phase may be used to detect the object.

In a eddy-current probe, stray eddy-currents from the probe coil are altered when the probe is in close proximity to a conductor. This will influence the loading on the coil and change the operating point on the resonant curve.

When a small area of resolution is required, the air gap between the coil and the conductive material must be minimized. This type of probe suffers similar limitations as the capacitive probe. The highest frequency response range found for probes using the inductive principle reached one MHz under ideal conditions. Conditions required included ferromagnetic material and stand off distances of approximately 0.005 inches.

2.3.3 Optical Probes

Optical techniques appear to offer the most promise in terms of frequency response and resolution. Their principle of operation is basically to detect reflective light from an object passing the probe. When distance between the object and the light source are to be measured, it is common to determine the intensity of the reflected light although measurement of the doppler shift and light interference patterns from two probes have been used.

The optical systems discussed in Section 2.2 were generally developed specifically for the evaluations discussed and were not considered simple and sufficiently reliable for long term continuous monitoring. The use of lasers as the light source also adds complexity and cost to the system. In reviewing the field for the availability of optical sensors, simplicity and economics were important criteria.

Of the available optical probes on the market, two techniques were found using the reflective light principle, i.e., glass optical fibers and a focused emitter and detector. The fiber-optic probes requires a light source and utilizes the fibers to transmit the light to the object. Reflective light is returned through a set of receiving fibers.

There are no standard fiber-optic probes available for the response and resolution required. McCarty and Thompson(9) report using a special fiber-optic probe system fabricated by General Electric. This is similar to the system reported by Nieberding and Pollack(6) where a sensitivity to angular displacements to 4.3 m rads was reported, compared to the present system requirements of 0.8 m rads. Standard fiber-optic probes are less suited for the required resolution and would require development modifications for the proposed application. In order to obtain the small area of resolution, a focused lens system appears the most practical approach when using fiber-optics. In order to attain the required intensity, a laser such as an Optical Information Systems semi-conductor diode laser may be required. These devices are currently used in high-frequency data communications to 275M.bytes/second. If this source was used on a transmission fiber, a very fast PIN photo-diode such as a HP5082-4200 series with one nanosecond response could be used as the detector from the receiving fiber-optic bundle.

The second optical device utilizes a LED emitter, a plastic lens and a matched I.C. photo-diode. The reported rise time of this sensor is 25 nsec. which is within the required range of the present application. This device is limited in temperature operation to 70°C because of the

plastic lens. With the exception of the temperature limit, this sensor is closer to meeting the requirements of the VA1310 Compressor System than other available optical sensors.

2.3.4 Wiegand Wire Sensor

The Wiegand Wire sensor is a relatively new concept consisting of a specially treated wire material that changes polarity and produces a voltage pulse when subjected to a magnetic field. The sensor consists of a wire pickup and two calibrated magnets housed in a non-magnetic material. The introduction of a ferrous material in proximity to the magnetic field produced by the magnets results in a polarity change of the wire resulting in a minimum 1.0 volt pulse without electrical power input. The generation of the pulse is independent of target velocity and results in a 20 microsecond pulse width.

Because this sensor does not rely on reflective surfaces it is potentially more reliable in terms of the extraneous signals. The rise time of 20 microseconds is considerably longer than the desired rise time and would require careful circuit design to obtain the desired resolution required.

2.4 Probe Evaluations

From the review of probe technqiues obtained from a literature search and market survey, optical techniques appear to offer the best approach in terms of resolution and response. On the other hand, their complexity, reliability and cost are questionable factors for continuous monitoring although the resolution and rise time are acceptable.

In order to establish the capabilities and limitations of available sensors, laboratory evaluations were conducted on the static and dynamic characteristics of a number of sensors. The sensors selected for evaluation were:

- Fiber optic probe (transmission and receiving)
- Fiber optic probe (transmission w/photo transistor receiver)
- LED emitter and photo-diode receiver
- Wiegand wire probe

The fiber-optic probes did not have the frequency response required for the present application. They were evaluated to determine their capabilities to detect the lead edge of the blade within the range of 0.001 to 0.003 inches without the use of a lens. If this resolution is possible, modifications to the probe electronics could be considered. The LED emitter probe is reported to have the required response time but is limited in temperature range. The Wiegand wire probe is the only non-optic probe considered for evaluation. Although the probe rise time does not meet application requirements, it may be possible to accept this characteristic through an improved detection circuit design.

Figure 4 depicts the probes selected for evaluation. From left to right, the probes are a LED emitter probe, Wiegand wire probe, two fiber-optic probes and the fiber-optic probe with photo-transistor receiver.

The following paragraphs summarize the static and dynamic evaluations conducted on the four probe types.

2.4.1 Experimental Procedure

Each probe was tested for sensitivity and diameter of resolution. A micrometer test fixture as shown on Figure 5 was used for these tests. The probe was installed in the axial position of the fixture and the micrometer head moved toward the probe. The probe output voltage was recorded as a function of probe gap between probe tip and micrometer head.

For measurements of diameter of resoltuion, the probe was installed in a position in the rig normal to the micrometer head observing the flat on the micrometer head. The probe gap was set at the optimum voltage output and the micrometer head was moved past the probe. The voltage output was recorded as a function of micrometer head position as it passed the probe. Figure 6 illustrates the test set up for these evaluations.

Figure 4 Probes selected for evaluation.

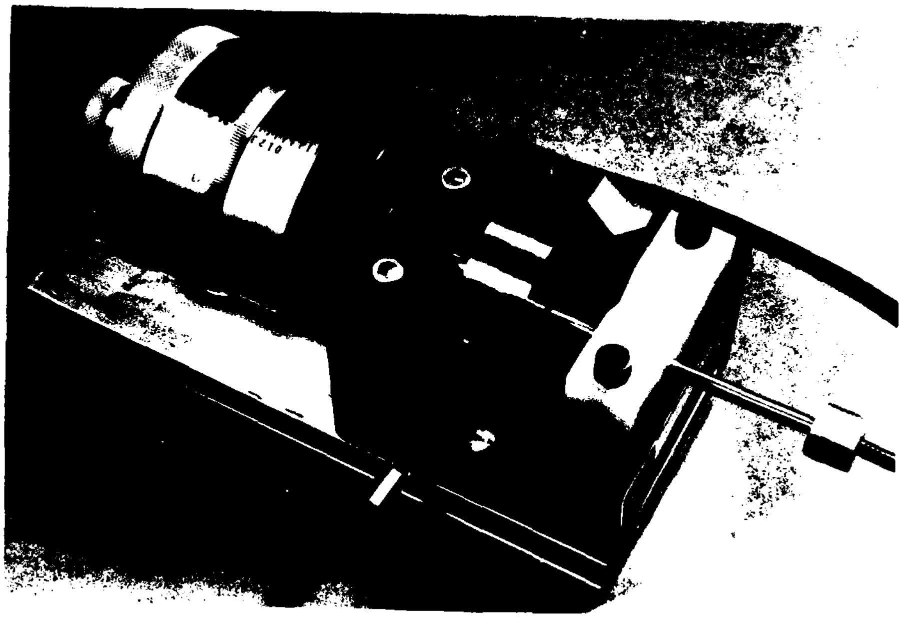

Figure 5   Micrometer Test Fixture

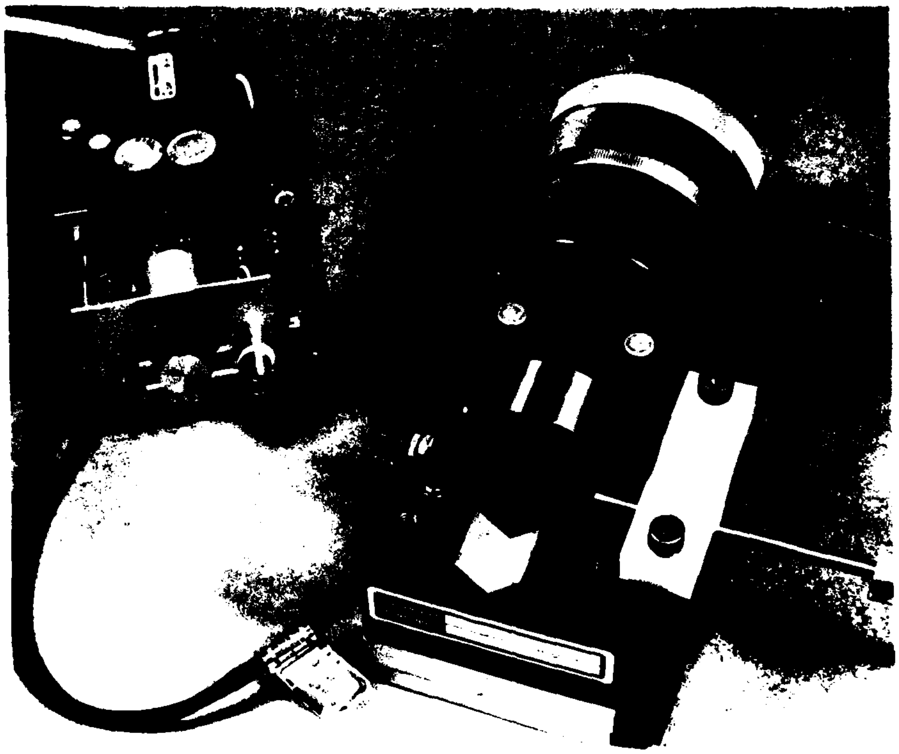

Figure 6 Measurement of Diameter of Resolution

In addition to static tests the probes were evaluated in an electric motor driven test rig as shown in Figure 7. The drive is a variable speed motor which turns the spindle at speeds to 30,000 rpm. The spindle contains a 3-inch diameter disc with two slots for detection of the lead edge of the slot by the sensor. The maximum surface velocity of the sensed disc is 4800 inches per second. Each probe was installed in the test rig and the rise time and stability of the leading edge of the probe was evaluated.

2.4.2 Fiber Optic Transmitter-Receiver Probe

Light from an incandesecent source is coupled into glass optical fibers comprising one-half of a bifurcated fiber optic cable in this type probe. The light travels the length of the bundle until it exits and is reflected from the target surface to the other half of the fiber cable. It travels down this bundle where it is coupled to a photo-diode/ amplifier circuit.

Two type probe configurations were evaluated, i.e., a circular fiber bundle and a rectangular shaped bundle. The purpose of the rectanglar bundle was to improve the edge resolution of the probe.

Static tests of both probes were conducted to establish probe sensitivity and edge resolution of a moving reflective surface. Figure 8 illustrates the probe sensitivity with gap and indicates a five-volt output with a gap in the range of 0.90 to 0.15 inches which is in the proper range for the required stand-off distance of the present application. Edge resolution was tested with two different orientations of the fiber bundle at a gap spacing of 0.1 inch. The best resolution occurred with the division line between transmitter and receiving bundles parallel to the passing target edge. An output of 180 mv per mil of displacement is possible using this probe. If it is assumed that a detector circuit is designed to sense midscale voltage of 2.5 volts, plus or minus 0.25 volts, the edge could be detected within 0.5 volts or 0.0028 inches.

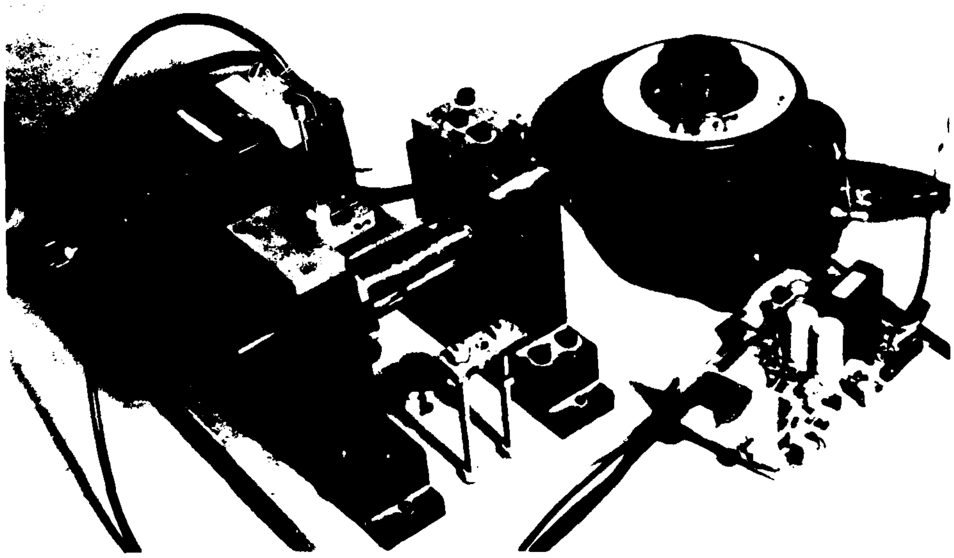

Figure 7   Dynamic Test Fixture

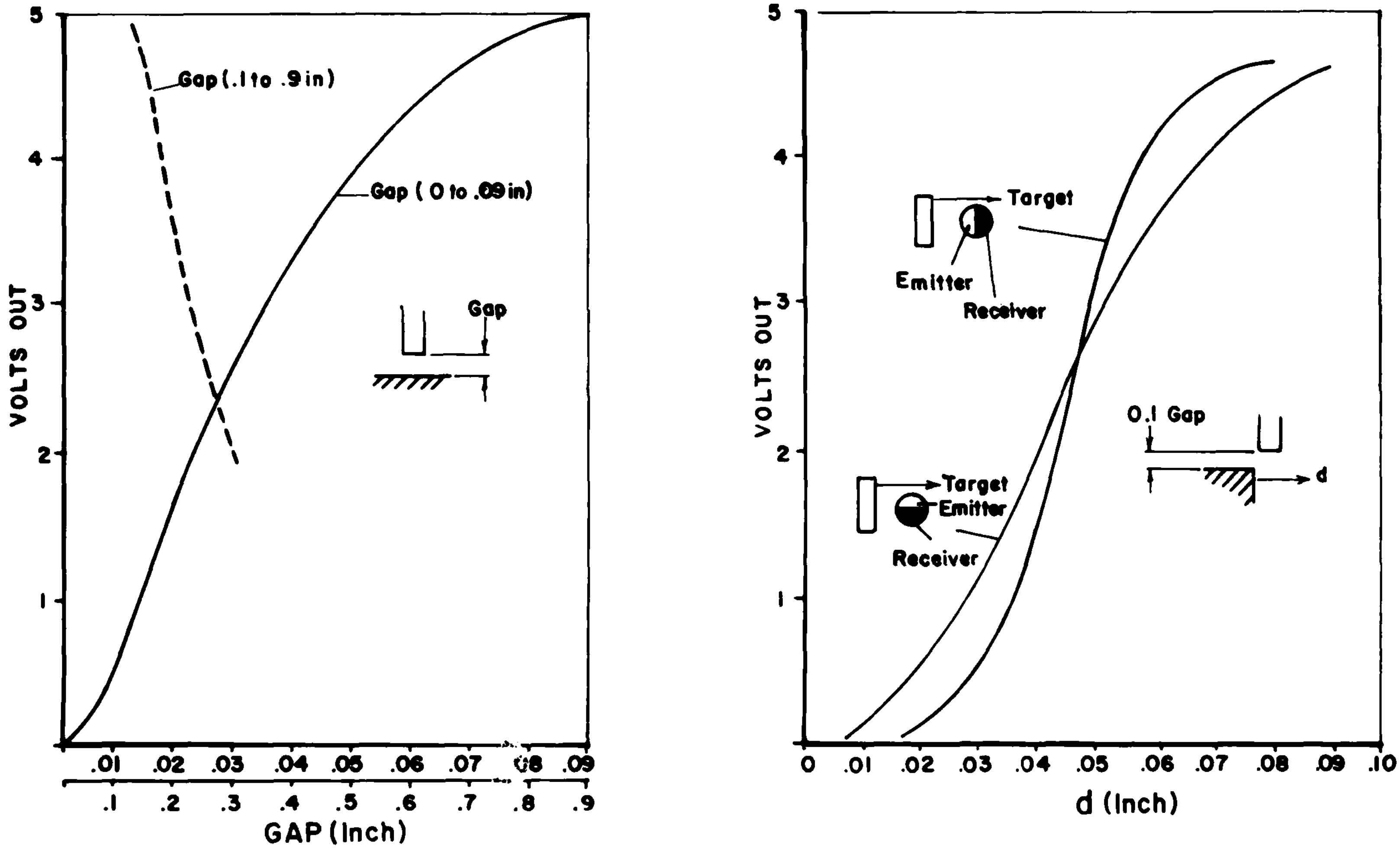

Figure 8 FIBER OPTIC PROBE - Circular Bundle

The retangular bundle probe has an output of 5.75 volts over the gap range from 0.023 to 0.275 inches as shown on Figure 9. Edge resolution with this probe was evaluated at gaps of 0.028, 0.06 and 0.08 inches. Voltage output changes as a function of distance the target moves past the probe were 0.4 v/mil, 0.39 v/mil and 0.36 v/mil respectively. This is a two-to-one improvement over the circular probe. Blade edge resolution of 0.0015 inch could be readily detected with this probe.

Dynamic testing of the probe in the rotating rig indicated a rise time of the probe of 20 microseconds. This limitation is imposed by the photo-diode response and circuit electronics. The probe appears to offer considerable promise in terms of edge resolution without the need for a lens but requires redesign of the electronics to obtain the required response time for the application.

2.4.3 Fiber-Optic Probe with Photo Transistor

The second probe evaluated was also a fiber-optic probe; however, the reflected infrared light was detected by a photo transistor at the probe tip. The location of the electronics in that area limits the operating temperature range to 158^{o}F. Static tests of this probe indicates an operating output of approximately 5 volts that decreases to 0.2 volts over the range in gap spacing between probe tip and target of .025 to 0.4 inches. At a stand off gap of 0.1 inch as the target passes the probe, the output voltage slope is 167.5 mv/mil of target movement. Using a detector voltage resolution of plus or minus 0.25 volts, the probe is capable of edge resolution of 0.003 inches. Optimum resolution occurs in the gap range of 0.030 inches. (See Figure 10.)

Dynamic tests of the probe in a rotating test rig indicates rise times of one microsecond. Limitations in rise time are due to circuit element response characteristics. Higher frequency response time would necessitate redesign of the probe.

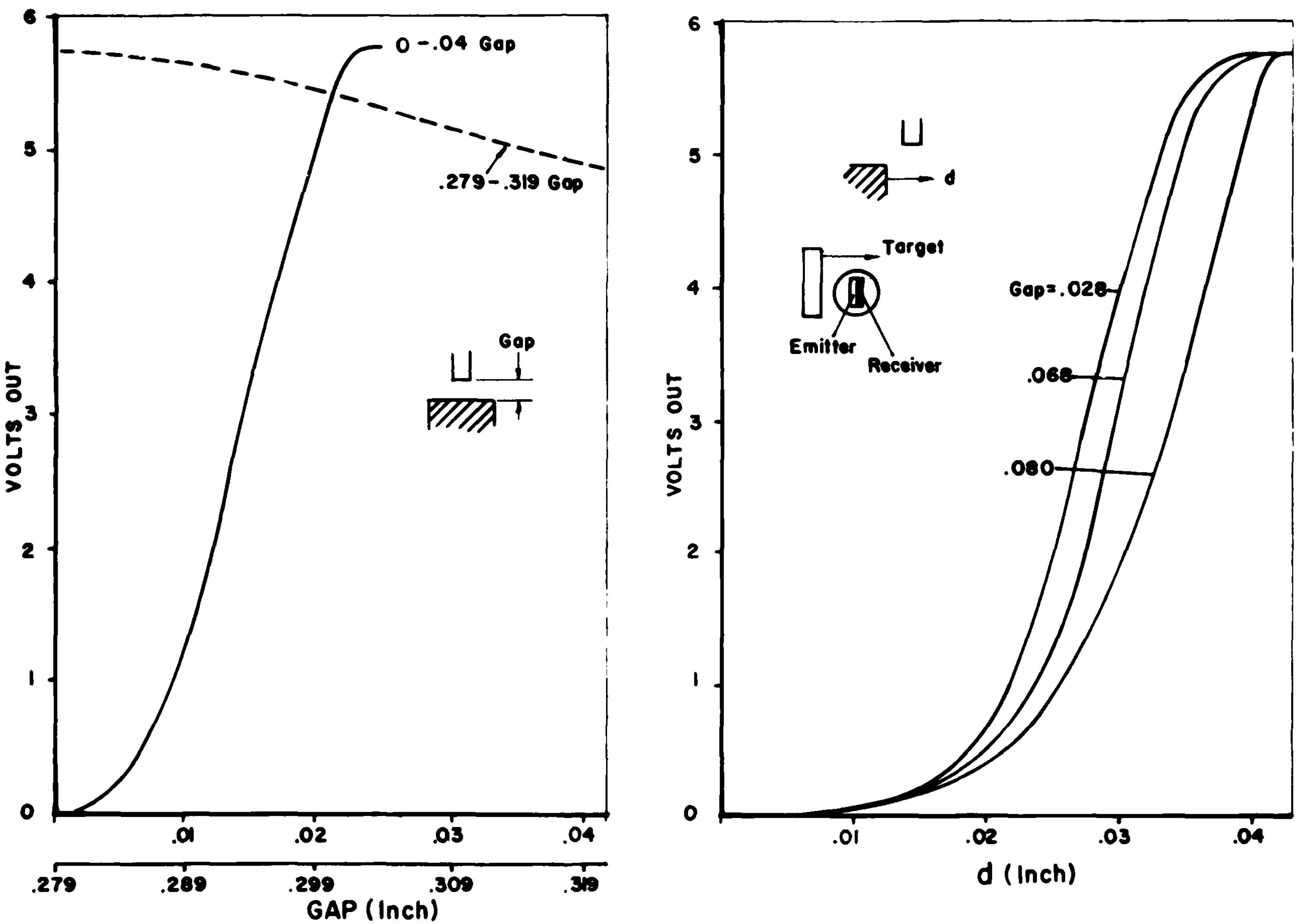

Figure 9 FIBER OPTIC PROBE - Rectangular Bundle

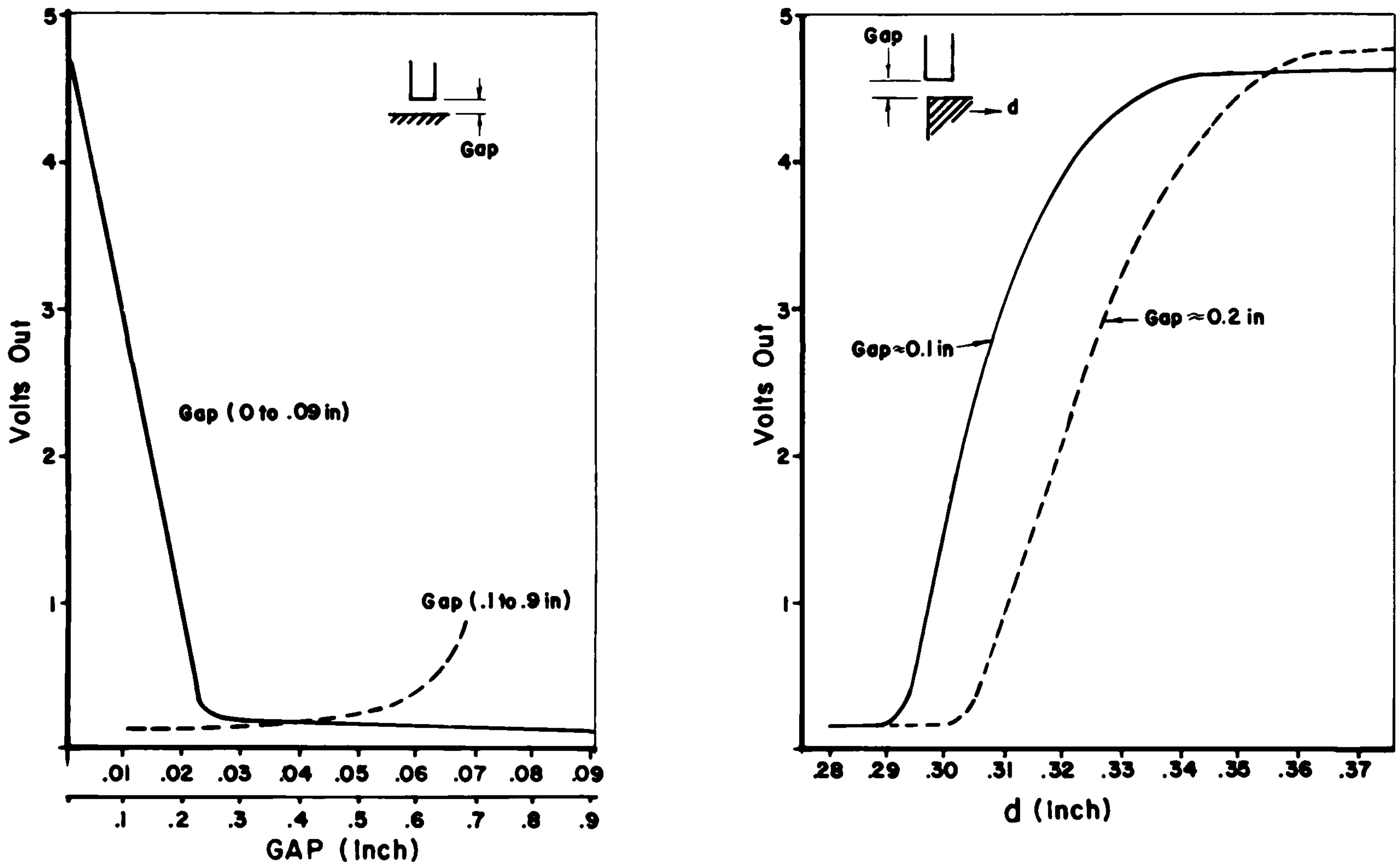

Figure 10 Fiber Optic Probe with Photo Transistor

2.4.4 LED Emitter and Photo-Diode Receiver

This probe is an integrated module designed for optical reflective sensing. The module contains a 0.007 in. diameter, 700 nm LED emitter and a matched I.C. photo-diode. A bifurcated acrylic lens images the active emitter and detector areas to a single spot 0.168 in. in front of the probe.

Figure 11 is a plot of the output voltage as a function of probe gap and of target passage by the probe. The output voltage from the probe is 1.6 volts at the optimum stand off of 0.168 inches a gap spacing of 0.155 inches, the change in voltage as a function of target spacing is 200 mv/mil. If a voltage detection circuit capable of detecting the mid voltage (0.6 volts) within plus or minus ten percent (±60 mv) is utilized with the probe, edge resolution to 0.0017 inches is possible.

The dynamic test rig operation was limited to 4800 inches per second. This surface velocity was not fast enough to accurately determine the rise time capabilities of the probe. The reported rise time by the manufacturer is in the range of 25 to 50 nanoseconds which is within the required range of the present application.

The use of a plastic lens limits operation of this probe below 158^{o}F. Other probe characteristics such as target edge resolution and pulse rise time are within usuable limits for the proposed application.

2.4.5 Wiegand-Wire Sensor

The Wiegand-Wire sensor differs markedly from the optical type sensors in that it delivers a voltage output pulse when in close proximity to a ferromagnetic material. The pulse is based on the behavior of a specially processed small diameter wire. The special short length wire is bi-stable magnetically. When subjected to a change in magnetic field, the wire changes magnetic states with a rapid internal flux

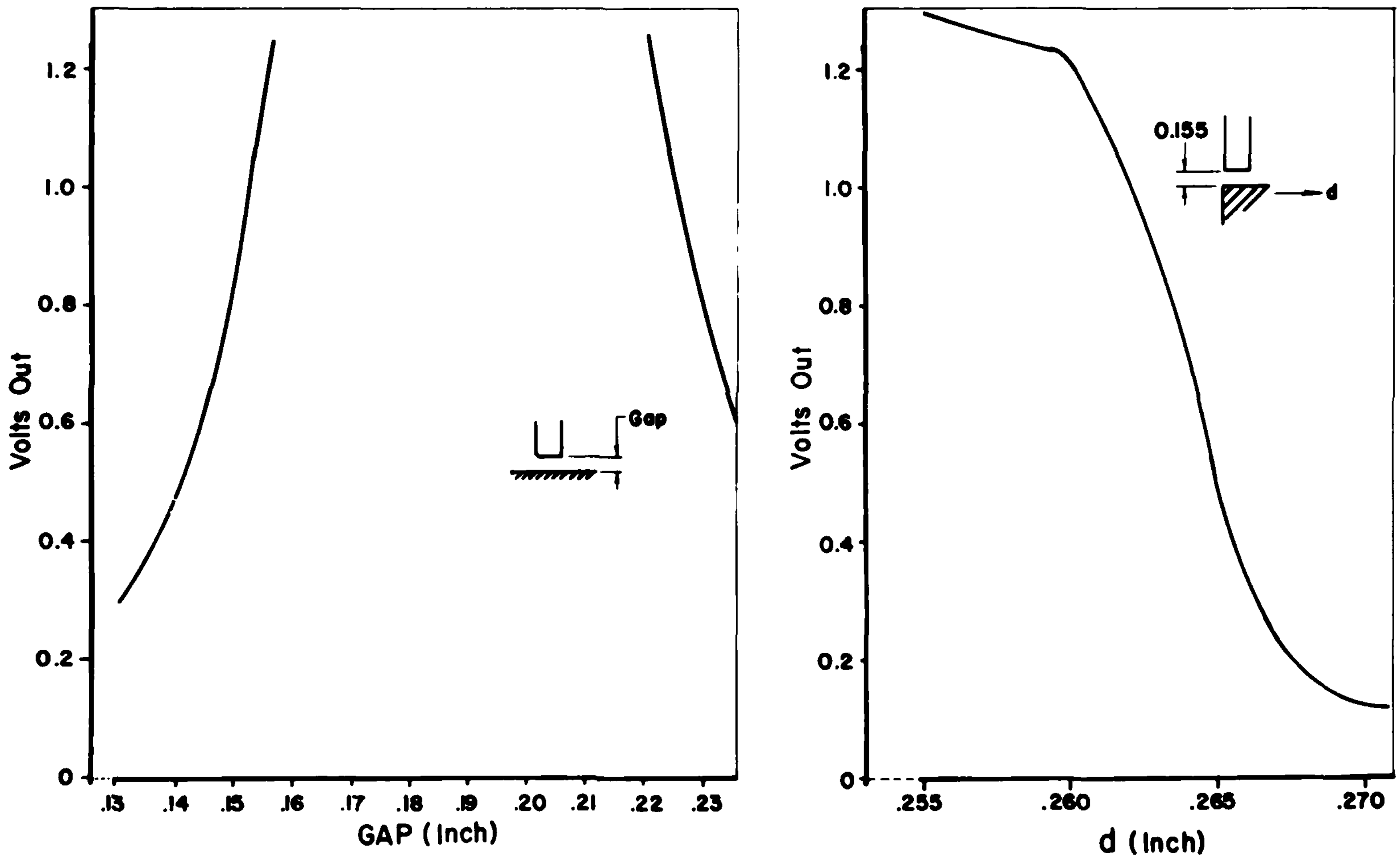

Figure 11 LED Emitter and Photo-Diode Receiver

jump. In probe form, a magnetic field is produced by two permanent magnets in the probe tip in close proximity to the wire. When a ferromagnetic material passes in close proximity to the probe, the field is shunted and the wire polarity switches inducing a pulse. Since the processed wire has a hard outer shell and soft inner core, the core switches first but the shell can also switch if the field polarity changes producing a negative pulse. In the probe, the negative pulse is a function of gap distance between target and probe. At small gaps (0.04 inches) positive and negative pulsing occurs while at larger gaps (0.06 inches) only positive pulses are produced.

The blade material used in the VA1310 Compressor is a 400 series stainless. Two blades were used to determine if the probe would work satisfactorily with this material. Stand off gaps from 0.04 inches to 0.10 inches were evaluated. The probe produced an output pulse of 2.0 volts at a gap of 0.075 inches but would no longer function as the gap increased to 0.08 inches.

Since the probe functions independently from speed, testing with high speed passage of a blade was not considered necessary. Passage of a blade tip statically was evaluated but repeatability of pulse occurrence was only within 0.006 inches. Rotating tests were conducted on the probe and resulted in variations in pulse arrival time of 10 microseconds. Figure 12 illustrates a typical pulse and indicates the pulse instability. This instability is attributed to the time response repeatability of the complex field switch of the wire. The 10 microsecond instability results in a blade edge resolution of 0.0905 inches. Tests were not conducted to determine the statistical characteristics of this instability. If the instability (or ten microsecond jitter) has a normal distribution in occurrence it would be possible to minimize the variations by statistically sampling the pulse arrival times. The manufacturer was contacted to determine if the statistical nature of the instability had been studied. It was indicated that no information regarding the statistical nature of the jitter has been developed. This knowledge is important in considering the suitability of the

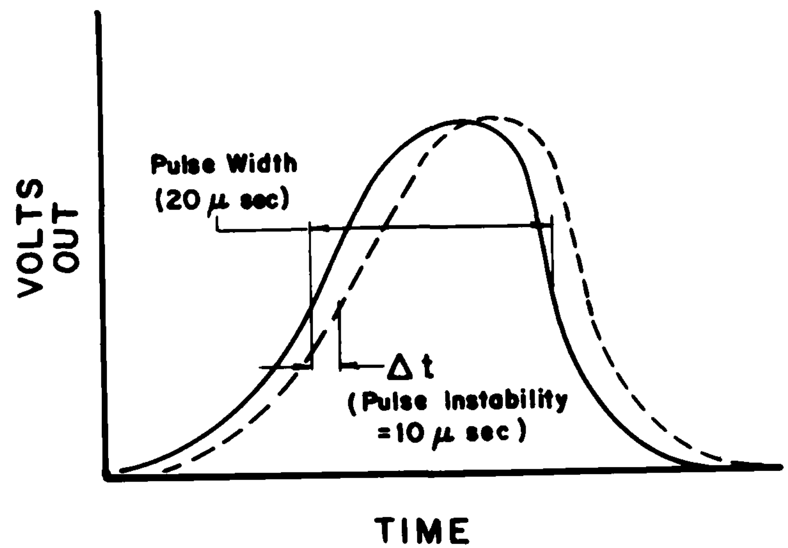

Figure 12   Wiegand Wire Pulse

Wiegand-wire for the present application. If the jitter is purely random, the mean arrival time from sampling the passage of one blade twenty-five times can improve the accuracy of the reading by an order of magnitude or greater. An improvement of 30 to 1 would be sufficient to consider the use of this device.

2.4.6 Summary of Probe Evaluations

From the results of evaluations of probes currently available on the market, it is apparent that a probe is not available that will meet all of the requirements for blade monitoring on the VA1310. In terms of frequency response, optical techniques appear to offer the greatest promise. Optical techniques are also the most common approach used to monitor blade vibrations in laboratory tests as reported from literature. It is also pointed out (References 2, 5 and 6) that optical techniques create problems from dust particles, from changes in reflectivity, and in complexity and cost.

The single technique evaluated that did not utilize optics was the Wiegand Wire. This device however has an inherent 10 microsecond variation in detecting blade arrival time. A statistical evaluation of this variation is required to determine the suitability of this type sensing technique before further consideration can be made.

2.5 Sensor Installation

No sensor was found that meets all of the requirements for the VA1310 compressor. The Wiegand Wire type of probe offers considerable advantage over optical techniques if the pulse arrival time from the probe can be evaluated statistically. A further concern with this probe or a optical sensor is the ability of installing the probe in the compressor assembly. Since the Wiegand Wire probe is a more difficult probe to install, in comparison to the optical probes, a layout of a typical installation was conducted to ensure that the probe could be installed in the compressor.

Drawings 375-D-400, 375-B-401, and 375-J-300 are appended to this report and illustrate the probe installation.* Once the probe is installed and the compressor reassembled, the probe is inaccessible and cannot be adjusted or replaced without disassembly. This points out the necessity for a very reliable probe that is relatively insensitive to probe to blade gap spacing. Because of the inner and outer case design of the compressor, the question of inaccessibility occurs despite the configuration of the probe that is used.

The installation drawings developed for the Wiegand Wire sensor could be readily modified to accept an optical sensor. They serve to verify that sensors can be installed in the compressor without imposing any degradation to the compressor structure or its performance characteristics.

*These drawings were prepared on the basis of blades provided to Shaker Research by WPAFB. Those blades are similar to but not identical to the blades on the VA310 compressor. The drawings for the probe installation may therefore require corrections prior to probe installation on the compressor.

3.0 CONCLUSIONS

A review was conducted of the availability of sensors that are suitable of meeting the requirements for a blade monitoring system for the VA1310 axial flow compressor. Optical techniques offer the most promise in terms of probe response time and measurement accuracy. Investigators applying optical techniques, as reported in literature, indicate concern when using these techniques, in long term reliability of optical systems and influences such as surface reflectivity changes and foreign particles inducing errors. It was generally concluded from literature that the optical techniques applied were not considered suitable for continuous, long-term monitoring and were more adaptable to laboratory testing.

A survey of available optical sensors was made to determine if a more rugged and reliable sensor might be available. Three different standard optical probes were selected for laboratory evaluations. Only one of the probes approached the performance requirements for the VA1310 compressor without modification. This probe however had a temperature limit of 72°C, which implies it would only be suitable for monitoring the first two compressor stage rows.

One sensor was evaluated that does not operate on the optical principle but utilized the "Wiegand Wire" effect. This approach offered considerable promise in terms of reliability and long-term stability. The probe however had a 10 microsecond variation in pulse arrival time, which appeared to be random in occurrence. Further evaluations would be required with this probe to determine the statistical characteristics of the probe before an assessment of its suitability to the application could be made.

From the study conducted, three sensor approaches could be considered for the proposed application; i.e.,

- A standard optical sensor presently available without modification could be used to monitor only the first two stages of the compressor.
- A fiber-optic sensor with a lens system could be developed that meets the performance requirements of the application. Difficulties might be encountered in the later stages of the compressor with this technique due to thermally induced surface reflectivity changes.
- Evaluations of the statistical characteristics of the Wiegand Wire sensor could be conducted to determine the suitability of this techniques.

4.0 RECOMMENDATIONS

Even though the Weignand wire probe as tested does not have the required pulse arrival time accuracy, it offers so many advantages as a blade crack detector that it should be pursued further to see if its defects can be corrected or compensated. It is possible that the errors noted in the probe test could be of two types. The first type is an error introduced by the probe design and construction method. This error source could be corrected or at least improved by better sensor design. The second type is associated with a possible inherent random nature to even the best implementation of the physical phenomenon. It is very likely that both sources of error are present. The following recommendations are therefore made:

1. The possibility of improved sensor design and manufacture be investigated with its manufacturer and Yale University who has conducted the most extensive sensor evaluations so far.
2. A sensor be fabricated as a result of recommendations made in the first task.
3. A simple test rig be constructed to allow testing sensors at the full blade arrival speeds.
4. The sensor resulting from Task 2 should be tested in the rig to ascertain the random signal character remaining.
5. Demonstrate the extent of signal accuracy improvement that can be achieved by statistical data processing techniques.
6. Demonstrate the accuracy of the optical probe in the same test rig.
7. Prepare a preliminary design for optical probe installation with provisions to keep the lenses clean.

Following these steps it is believed that the Flight Dynamics Laboratory personnel can make an informed decision to proceed with the full system, a partial system, or none at all.

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